Swift - Multiblock Analysis Code for Turbomachinery

User's Manual and Documentation

Version 110, January 16, 2002

Dr. Rodrick V. Chima
NASA Glenn Research Center, MS 5-10
21000 Brookpark Road
Cleveland, Ohio 44135 USA

phone:	216-433-5919
fax:	216-433-5802
email:	fsrod@grc.nasa.gov
internet:	http://www.grc.nasa.gov/WWW/5810/webpage/rvc.htm

Introduction

Swift is a multiblock computer code for analysis of three-dimensional viscous flows in turbomachinery. The code solves the thin-layer Navier-Stokes equations using an explicit finite-difference technique. It can be used to analyze linear cascades or annular blade rows with or without rotation. Three turbulence models are available. Limited multiblock capability can be used to model tip clearance flows and multistage machines.

Swift has been tested on numerous fan and turbine blades and has been used heavily at NASA Glenn Research Center for fan analysis and design, analysis of turbine endwall heat transfer, and many other applications. Swift is a multiblock version of RVC3D, which was originally described in (2) along with calculations of a blunt fin and an annular turbine. The flow equations, numerical method, and calculations of a transonic fan were given in (3). The algebraic turbulence models and calculations of turbine endwall heat transfer were described in (4), and the k-ω turbulence model was described in two-dimensions in (5). The multiblock code known as Swift was introduced in (6) along with calculations made of tip clearance flow in a transonic compressor. The preconditioning scheme and calculations of a large low-speed centrifugal impeller were described in (7). Finally, the multistage capability was described in (8) along with calculations of a two-stage turbine.

This report serves as the user's manual and documentation for Swift. The code and some aspects of the numerical method are described. Steps for code installation and execution are given for both Cray computers and workstations. The grid, input, and output variables are described in detail.

Features of Swift

- **Applications**
  Linear cascades
  Axial compressors and turbines
  Isolated blade rows or multistage machines
  Centrifugal impellers and mixed-flow machines without splitters
  Radial diffusers
  Pumps
- **Multi-block Capability**
  C-grids around blades
  H-grid upstream
  O-grids in hub- or tip-clearance regions (or periodic clearance model)
  Mixing-planes between blade rows
- **Formulation**
  Navier-Stokes equations written in Cartesian coordinates with rotation about the x-axis
  Thin-layer equations in streamwise direction, all cross-channel viscous terms retained
  Second-order finite-difference discretization
- **Turbulence Models**
  Baldwin-Lomax (algebraic)
  Cebeci-Smith (algebraic)
  Wilcox’s k-ω (two-equation)
  Surface roughness effects in all models
- **Numerical Method**
  Explicit multi-stage Runge-Kutta scheme
  Variable time-step and implicit residual smoothing for convergence acceleration
  Preconditioning for low-speed (incompressible) flows
- **Input**
  General grid files in PLOT3D format, usually generated using TCGRID
  Namelist input of flow parameters
- **Printed Output**
  Residual history
  Spanwise output of circumferentially-averaged flow quantities at the grid inlet and exit
  Streamwise output of blade surface properties
- **Computer Requirements**
  Runs as a batch process on most workstations or mainframe computers
  Fully vectorized and autotasked for SGI and Cray computers
  Runs well under linux, has been run under Windows
  Solution times range from one to several hours on modern workstations
  Written in FORTRAN, requires a FORTRAN compiler
- **Graphical Output**
  No graphical output is provided. Grid and solution files are in standard PLOT3D format and can be read directly and plotted with public-domain CFD visualization tools PLOT3D and FAST, or the commercial tools EnSight, FIELDVIEW, or TECPLOT. TECPLOT is currently the only package that is available for Windows.
  A utility that can make line plots from an ascii dataset is also useful.

.

k	α^1	α^2	α^3	α^4	α^5	λ^*
2	1.2	1.				.95
3	.6	.6	1.			1.5
4	.25	.3333	.5	1.		2.8
5	.25	.1667	.375	.5	1.	3.6

Table 1 - Runge-Kutta parameters $\alpha^1 - \alpha^5$ and maximum Courant number λ^* for *k* stage schemes.

Numerical Method

Multistage Runge-Kutta Scheme

Multistage schemes were developed by Jameson, Schmidt, and Turkel (10) as a simplification of classical Runge-Kutta integration schemes for ODE’s. The simplification reduces the required storage, but also reduces the time-accuracy of the schemes, usually to second order. The following discussion of these schemes should give some guidance in choosing parameters for running the code.

A k-stage scheme may be written as:

$$q^k = q^0 - \alpha^k \Delta t (R_I^k + R_V{}^0)$$

where *q* is an array of five conservation variables (see “Solution Q-File”, pp. 22), *k* is the stage count, q^0 is the previous time step, α^k are the multistage coefficients discussed below, Δt is the time step, R_I^k is the inviscid part of the residual, and $R_V{}^0$ is the viscous part of the residual including the artificial dissipation. Note that R_I^k is evaluated every stage, but $R_V{}^0$ is evaluated only at the initial stage for computational efficiency.

The maximum stable Courant number λ^* for an n-stage scheme can be shown to be $\lambda^* = n - 1$. The actual stability limit depends on the choice of α^k. For consistency α^n must equal 1, and for second-order time accuracy α^{n-1} must equal *1/2*. The values of α^k used in the code and the theoretical maximum Courant number λ^* are set by a **data** statement in subroutine setup and are given in table 1.

The number of stages is set with the variable *nstg*. Using $nstg = 4$ is recommended, although Jameson et. al. tend to favor 5 stages. Updating the physical and artificial viscosity terms more often increases the robustness of the multistage schemes, but also increases the CPU time per stage. Setting *ndis=2* causes the 4-stage scheme to update the dissipative terms during stages 1 and 2, and causes the 5-stage scheme to update them during stages 1, 3,and 5. A good compromise is *nstg=4* and *ndis=2.*

A spatially-varying Δt is used to accelerate the convergence of the code. Setting $ivdt = 1$ causes the Courant number to be set to a constant (input variable *cfl*) everywhere on the grid. The spatially-varying Δt option is highly recommended. For a multiblock grid the time step is recalculated every iteration. For a single block grid the time step is stored and recalculated every *icrnt* iterations. Set *icrnt* to a moderate number, e.g. 10, so that the time step is recalculated occasionally. The time step is recalculated when the code is restarted and may cause jumps in the residual if *icrnt* is too big.

Implicit residual smoothing (described later) may be used to increase the maximum Courant number by a factor of two to three, thereby increasing the convergence rate as well.

Artificial Viscosity

The code uses second-order central differences throughout and requires an artificial viscosity term to prevent odd-even decoupling. A fourth-difference artificial viscosity term is used for this purpose. This term is third-order accurate in space and thus does not affect the formal second-order accuracy of the scheme. The input variable *avisc4* scales the fourth-difference artificial viscosity, and should be set between 0.25 and 2. Start with *avisc4=1.0*. If the solution is wiggly, increase *avisc4* by

0.5. If it is smooth, try reducing avisc4 by 0.5. Larger values of *avisc4* may improve convergence somewhat, but the magnitude of *avisc4* has little effect on predicted losses or efficiency.

The code also uses a second-difference artificial viscosity term for shock capturing. The term is multiplied by a second difference of the pressure that is designed to detect shocks. Note that the second-difference artificial viscosity is first-order in space, so that the solution reduces to first-order accurate near shocks. Two other switches developed by Jameson (10) are used to reduce overshoots around shocks. The input variable *avisc2* scales the second difference artificial viscosity, and should be set between 0. and 2. Use 0. for purely subsonic flows, and start with *avisc2=1.0* for flows with shocks. If shocks are wiggly, increase *avisc2* by 0.5. If they are smeared out, try decreasing *avisc2* by 0.5. Shocks will be smeared over four or five cells regardless of the value of *avisc2*. The magnitude of *avisc2* also has little effect on predicted loss or efficiency.

Eigenvalue scaling described in (3) is used to scale the artificial viscosity terms in each grid direction. This greatly improves the robustness of the code. The artificial viscosity is also reduced linearly by grid index near walls to reduce its effect on the physical viscous terms. Input variables *jedge, kedgh,* and *kedgt* are the indices where the linear reduction begins.

A first-order artificial viscosity term may be added to smooth the solution drastically during solution start-up. The variable *avisc1* scales this term. First-order artificial viscosity will greatly improve the convergence rate while greatly diminishing the accuracy of the solution. It will thicken boundary layers, smear shocks, and greatly increase predicted loss. Do not use first-order artificial viscosity except to start a new solution. A warning is printed in the output when $avisc1 > 0$.

Implicit Residual Smoothing

Implicit residual smoothing was introduced by Lerat in France and popularized by Jameson in the U.S. as a means of increasing the stability limit and convergence rate of explicit schemes. The idea is simple: run the multistage scheme at a high, unstable Courant number, but maintain stability by smoothing the residual occasionally using an implicit filter. The scheme can be written as follows:

$$(1-\varepsilon_\xi\delta_{\xi\xi})(1-\varepsilon_\eta\delta_{\eta\eta})(1-\varepsilon_\varsigma\delta_{\varsigma\varsigma})\bar{R} = R$$

where ε_ε, ε_η, and ε_ς are constant smoothing coefficients in the three body-fitted coordinate directions ε, η, and ς indicated in figure 1. Here δ is a second-difference operator, $\bar{R}$ is the smoothed residual, and *R* is the unsmoothed residual.

It can be shown that if the scheme converges, implicit residual smoothing does not change the solution. Linear stability theory shows that the scheme can be made unconditionally stable if ε_i is big enough, but also shows that the effects of the artificial viscosity are diminished as the Courant number is increased. In practice the best strategy seems to be to double or triple the Courant number of the unsmoothed scheme. If the residual is smoothed after every stage, the theoretical 1-D values of ε_i needed for stability are given by:

$$\varepsilon_i \ge \frac{1}{4}\left[\left(\frac{\lambda}{\lambda^*}\right)^2 - 1\right]$$

where λ^* is the Courant limit of the unsmoothed scheme (given in the previous table,) and λ is the larger operating Courant number. For example, to run a four-stage scheme at a Courant number $\lambda = 5.6$, the smoothing coefficient should be:

$$\varepsilon_i \ge \frac{1}{4}\left[\left(\frac{5.6}{2.8}\right)^2 - 1\right] = 0.75$$

A single variable $eps = \varepsilon$ is input to Swift. The 1-D limit given above usually gives a reasonable estimate for ε, but the code will converge best when ε is minimized. Values of ε_ε, ε_η, and ε_ς are evaluated at each grid point within the code by scaling *eps* using the same Eigenvalue scaling coefficients used for the artificial dissipation. This has proven to be quite robust.

In rare cases it may be necessary to increase the residual smoothing coefficient in a particular direction. This can be accomplished using input variables *epi, epj,* and *epk,* which are constants (usually 1.) that multiply ε_i at each point.

Implicit residual smoothing involves a scalar tridiagonal inversion for each variable along each grid line in each direction. It adds about 20 percent to the cpu time when applied after each stage. Smoothing can be done after every other stage to reduce cpu time (about 7 percent,) but *eps* must be increased (approximately doubled.)

Recommended starting values are: $nstg = 4$, $cfl = 5.6$, $irs = 1$, and $eps = 0.75$. If the code blows up quickly try increasing *eps* to 1.5. Very large values of *eps* (e.g. > 3) may stabilize a stubborn calculation but prevent the residuals from decreasing. If the residuals drop a little then climb to a large, constant value, *eps* is probably too big and the solution is probably incorrect.

Preconditioning

Density-based schemes like Swift solve the continuity equation by driving the density residual to zero. For low speed (nearly incompressible) flows the density residual is physically near zero, and the schemes fail to converge. Preconditioning, described by Turkel in (12) improves the convergence rate in two ways. First, it replaces the q-variables $q = [\rho, \rho u, \rho v, \rho w, e]$ with variables that are better-behaved at low speeds $W = [p, \rho u, \rho v, \rho w, h]$, where p is the pressure and h is the total enthalpy. Second it multiplies the equations by a matrix designed to equalize the wave speeds of each equation. The preconditioning matrix has the local flow velocity in the denominator and must be limited when the velocity becomes small. The preconditioning operator is designed so that it has no effect on the steady-state solution.

Preconditioning works extremely well for the Euler equations and less well for the Navier-Stokes equations. It will allow solutions at very low speeds that simply would not work otherwise.

Grids

Swift can handle single-block grids and a limited variety of multi-block grids. Grids are usually generated using TCGRID (9). Grids **must** include all dummy grid lines (unlike RVC3D which generated a dummy grid line internally.) In TCGRID, dummy grid lines are included by setting *iswift=1* in namelist 5. Grids are stored in standard PLOT3D format(see “Grid XYZ-File”, pp. 22.)

Isolated Blade Row Grid

The basic Swift grid consists of a C-type grid around a blade, as shown in figure 1. The i- or ξ-direction goes from i=1 at the lower exit to i=im at the upper exit. The j- or η-direction goes from j=1 at the blade to j=jm-1 at the periodic boundary (j=jm at the dummy grid line.) The k- or ζ-direction goes from 1 at the hub to k=km at the tip. Calculations run with a single grid avoid some data I/O and thus run about 15 percent faster than a multiblock grid with the same number of points.

An H-type grid can be added to extend the grid upstream, as shown in figure 2. O-type grids can be used to resolve the hub or tip clearance regions of blade as shown in figure 3. Clearance regions can also be modeled using a simple periodic boundary condition that does not require gridding the region (6.) The connectivity between the grids is specified using an index file (see “Index File”, pp. 18.)

Multistage Grids

Using TCGRID, multi-stage grids must be generated row-by-row. A grid for a two-stage turbine is shown in figure 3, and a detailed view is shown in figure 2.

The meridional grid must be continuous across multistage grids. This means that all grids must have identical hub and casing coordinates *zhub*, *rhub*, etc., identical number of spanwise points *km*, identical spanwise spacing parameters *dshub*, *dstip*, etc., and identical clearance parameters. Neighboring grids must have matching downstream/upstream boundary coordinates *zbc*, *rbc*. Future versions of Swift may include interpolation between non-continuous meridional grids.

Blades must be oriented correctly in the θ-direction and placed in their correct axial location. TCGRID variables *zscale*, *tscale*, *rscale*, *ztrans,* and *tflip* will help with blade placement.

Dummy grid lines must overlap the neighbors exactly one cell, as shown in figure 2. Dummy grid lines are included in TCGRID files if *iswift=1*. The spacing ahead of the inlet is set using *dsmax*. The spacing at the exit can be set using *dslap*. Thus *dslap* for the upstream grid must equal *dsmax* for the downstream grid. It may take a few iterations to get nicely overlapping grids. It may help to start with the downstream grid and work upstream.

Grid files from neighboring blade rows are combined into a multi-block PLOT3D file using the included utility routine MULTIX, which prompts for file names and should be self-explanatory. TCGRID generates index files for each blade row. These must be merged manually using an editor.

Compiling and Running Swift

Swift is distributed as a unix script which generates the source and include files and compiles them. The format of the script file is shown below.

```
#! /bin/csh -f
cat > Swift.f << '/eof'
#Swift source code goes here
'/eof'
#--------------------------------------------------------
cat > noncray << '/eof'
#two replacements for Cray-specific routines go here
'/eof'
#--------------------------------------------------------

cat > param << /eof
#code dimensioning parameters go here
       parameter(ni=185,nj=37,nk=49,mg=3,idb=370000)      !Rotor 67
/eof
#--------------------------------------------------------
cat > csca << /eof
#scalar common block goes here
eof
#--------------------------------------------------------
#other common blocks follow
#--------------------------------------------------------
#compiler commands with options go here
f90 -O3 -mips4 -lfastm -o swift swift.f noncray.f
```

On a unix platform, edit the script and go to the bottom. Change the parameter statements to values greater than or equal to the size of the grid to be run. (See *Parameter Statements* below.) Comment, uncomment, or add compilation commands appropriate for the computer to be used. (See below for compilation commands for SGI and Cray computers.) Save the script, set execute permission, and execute it.

On a PC, manually strip out, save, and compile the files between the *cat* and */eof* commands.

Parameter Statements

Swift uses a single parameter statement to make redimensioning simple. In fact, it is usually advantageous to redimension Swift to exactly the grid size needed for a particular problem. The parameter statement and labeled common blocks are inserted during compilation using Fortran include statements. A typical parameter statement is shown above. Actual parameter values may be different in the distribution code. Swift checks the user input against the dimensioning parameters and stops with a fatal error message if the code is not dimensioned properly. The parameters are defined as follows:

ni, nj, nk	Dimensions of working arrays. Many working arrays are dimensioned array(ni,nj,nk) and must be large enough to contain any of the individual grids in a multiblock grid. In other words, $ni \geq max(imax_n)$, etc., where $imax_n$ is the largest i-index of any of *n* grids.
mg	$mg \geq$ number of grids. The storage associated with *mg* is insignificant, so *mg* can be left large if desired.
idb	Dimensions of buffer arrays. $idb \geq \sum_n imax_n \times jmax_n \times kmax_n$. In other words, idb must be big enough to hold ALL of the grid points of the multiblock grid. For a single block grid, $idb \geq imax \times jmax \times kmax$.

Thirty-six variables are stored in working arrays, and 12 variables are stored in buffer arrays. Thus the computer memory required to run RVCQ3D is $36 \times ni \times nj \times nk + 12 \times idb$ floating point words for arrays, plus about 300K words for the executable code. For a single block grid the total array storage is 48 times the grid size, plus about 300K words.

Compiling Swift on Silicon Graphics Workstations (IRIX)

The following commands can be used to compile Swift on an SGI Octane workstation:

```
    #SGI R12000 CPU
    f90 -O3 -mips4 -lfastm -o swift swift.f noncray.f
    strip swift
```

Compiling Swift on Cray Research Computers (UNICOS)

The following command will compile Swift on a Cray C-90:

```
     f90 -O aggress,scalar3,vector3,task3 -o swift swift.f
```

Swift will autotask (run on multiple processors) on the C-90 when the environment variable NCPUS is set.

setenv NCPUS 6

Running Swift

The executable program is run as a standard unix process:

```
    Swift < std_input > std_output &
```

Standard Input, Output and Other Files

An ascii input file for Swift is read from Fortran unit 5 (standard input.) Printed output from Swift is written to Fortran unit 6 (standard output.) Files linked to Fortran units 1-4 and 7-15 may be used in the execution of Swift, depending on input options. The units are used as follows:

fort.1binary input grid file, required (see “Grid XYZ-File” pp. 22.)
fort.2 binary input solution file, read if *iresti* = 1 . (see “Solution Q-File” pp. 22.)
fort.3binary output solution file, written if *resto* = 1. (see “Solution Q-File” pp. 22.)
fort.10ascii index file, required. (See “Index File” pp. 18.)

fort.7binary input kw file, read if *ilt = 4 or 5* (see “Turbulence Model k-w File”, pp. 22.)
fort.8binary output kw file, written if *ilt = 4 or 5* (see “Turbulence Model k-w File”, pp. 22.)

fort.13 ascii input qin file, read if *iqin = 1* (see “Inlet and Exit Profiles”, pp. 22.)
fort.14 ascii input pex file, read if *ipex = 1* (see “Inlet and Exit Profiles”, pp. 22.)
fort.15 ascii output span file, written if *ispan = 1* (see “Inlet and Exit Profiles”, pp. 22.)

All files are treated as unformatted ascii or binary files. They are not explicitly *opened* in the code. Files are usually linked to file names before running Swift,

```
    ln input.grid.file fort.1
    ln input.solution.file fort.2
    #etc.
```

Binary files generated on an SGI machine can be read into PLOT3D using the *read /unformatted* option. Files generated on a Cray can be converted to SGI format in one of two ways:

1. (Preferred,) by *assigning* the files as 32 bit ieee binary files on the Cray before execution. The lower precision does not affect the accuracy of Swift. Files written on a Cray while assigned as ieee binary can be used directly on an SGI machine and can be read into PLOT3D using the *read /unformatted* option.

```
    assign -F f77 -N ieee fort.1
    assign -F f77 -N ieee fort.2
    #etc.
```

2. (Outdated,) by using the *itrans* command at NASA Ames to convert the files to SGI binary. Files converted using *itrans* can be read into PLOT3D using the *read /binary* option <default>.

```
itrans file.xyz file.SGI.xyz
irisbin -u -v file.xyz file.SGI.xyz
```

Ref. State	English Units	SI Units
P_{0r}	2116.8 lb_f/ft^2	1.0135 x 10^5 Pa
T_{0r}	519 R	288.3 K
c_{0r}	1116.7 ft/sec	340.39 m/sec
ρ_{0r}	.0765 lb_m/ft^3	1.2246 kg/m^3
μ_{0r}	1.285 x 10^{-5} lb_m/(ft sec)	1.91 x 10^{-5} kg/(m sec)
$Renr$	6.65 x 10^6 [1/ft] 5.54 x 10^5 [1/in]	2.182 x 10^7 [1/m] 2.182 x 10^4 [1/mm]

Table 2 — Standard reference quantities usually used for nondimensionalization.

Non-Dimensionalization

The grid *xyz*-file may be input in arbitrary units of length. The input parameters to Swift and the variables in the output *q*-file are strictly nondimensional, with the exception of lengths which must have the same units as the grid.

All quantities are nondimensionalized by an arbitrary reference stagnation state defined by stagnation density ρ_{0r}, sonic velocity c_{0r}, and viscosity μ_{0r}, where μ_{0r} is defined at the stagnation temperature $T_{0r} = c_{0r}^2 / (\gamma R)$. Standard atmospheric conditions, given in table 2 above, are often used for the reference state. However, *any* self-consistent state may be used as long as the units of length are consistent with the grid units.

Input pressures and temperatures are nondimensionalized by P_{0r} and T_{0r}, respectively. Within the code pressures are usually nondimensionalized by $\rho_{0r} c_{0r}^2 = \Upsilon P_{0r}$. Inlet pressures and temperatures are nondimensionalized similarly, so that $P_{0in} = T_{0in} = 1$ for cases in which the inlet is at standard conditions. However, P_{0in} and T_{0in} can also be set arbitrarily using the initial condition input (see “Initial Condition Input”, pp. 17) or a *qin* file (see “Inlet and Exit Profiles”, pp. 22.) Input velocities are sometimes nondimensionalized by c_{0r} and sometimes input as a Mach number.

The reference state defines a reference Reynolds number *Renr* which must be input to Swift (see “&nam5 - Viscous Parameters”, pp. 15.) *Renr* is given by $renr = \rho_{0r} c_{0r} / \mu_{0r}$ and has units of [1/grid units.] *Renr* remains the same for all cases with the same reference state and grid units.

Output quantities should be self explanatory, except for the mass flow. The mass flow may be output with the residual history (see “&nam6 - Output Control”, pp. 16, variable *mioe*.) Mass flow is also output in the tables labeled “theta-averaged quantities,” at the bottom of the column labeled “% mdot.” In either case, the mass flow is nondimensionalized by $\rho_{0r} c_{0r}$ and has units of [grid units]^2. The mass flow through the full annulus is given (rather than mass flow per passage,) so that the printed mass flow should be constant through a multistage machine.

Swift Input

Namelist input is used for most variables. Many variables have defaults assigned and can be defaulted (not input.) Defaults are given in angle brackets, <Default=value> or <default.> If no default is given the value MUST be input.

Title

ititle	An alphanumeric string of 80 characters or less printed to the output. The character string must be enclosed in single quotes.

***&nam2* - Algorithm Parameters**

nstg	Number of stages for the Runge-Kutta scheme, usually 4, but can be 2-5. <default = 4>
ndis	Number of evaluations of artificial viscosity per stage. More than one evaluation usually improves robustness but increases CPU time. <default = 1> ndis > 1 gives 2 evaluations at stages 1 and 2 for *nstg = 4*. ndis > 1 gives 3 evaluations at stages 1, 3, and 5 for *nstg = 5*.
cfl	Courant number, typically 5.6 (see “Multistage Runge-Kutta Scheme” pp. 3.) If $ivtstp = 0$, *cfl* is the maximum Courant number, usually located somewhere near the leading edge at the blade surface. If $ivtstp = 1$, the Courant number will equal *cfl* everywhere. <default = 5.0>
avisc1	First-order artificial dissipation coefficient. Usually 0., but can be used to stabilize a solution that blows up at startup. Set $avisc1 = 1.$ for the first 50 or so iterations if necessary, but be sure to set $avisc1 = 0.$ as soon as the solution is running stably. (see “Artificial Viscosity”, pp. 3.) <default = 0.0>
avisc2	Second-order artificial dissipation coefficient. Typically 0. - 2. Use 0. for purely subsonic flow or 1. for flows with shocks. <default = 0.5>
avisc4	Fourth-order artificial dissipation coefficient. Typically 0.25 - 1.5. Start at 1.0 and reduce *avisc4* to 0.5 if possible. <default = 0.5>
irs	Implicit residual smoothing flag. Usually = 1. (See “Implicit Residual Smoothing” pp. 4.) = 0 No residual smoothing. = 1 Implicit smoothing after every Runge-Kutta stage <default.> = 2 Implicit smoothing after every other stage. *eps* must be increased for this option to work.
eps	Overall implicit smoothing coefficient based on the 1-D stability limit (see “Implicit Residual Smoothing”, pp. 4) Swift will calculate the 1-D limit if *eps* is defaulted.
epi, epj, epk	Implicit smoothing coefficient multipliers for the *i, j,* and *k* directions. (see “Implicit Residual Smoothing”, pp. 4) Rarely used. <default = 1.>
itmax	Number of iterations, typically 50-1000 per run, but 1000-3000 may be needed for a converged solution.
ivdt	Variable time step flag. = 0 Spatially constant time step. = 1 Spatially variable time step. <default, highly recommended>
ipc	Preconditioning flag, (see “Preconditioning” pp. 5.) = 0 No preconditioning. <default>

	= 1 Preconditioning using the Merkel, Choi, Turkel scheme. Should give a substantial speedup for Mach numbers < 0.3.
	= 2 Solves the equations using the preconditioning variable set, but sets the preconditioning matrix to the identity matrix. Used to debug the preconditioning routines.
pck	Constant limiter (Turkel's parameter *k*) for preconditioning. The denominator in the preconditioning matrix is limited to be > $pck \times q'_{\mathrm{ref}}$. Typically 0.1 - 0.3, but larger values may be necessary for stability. <0.15>
refms, refmr	Reference relative Mach numbers used to find q'_{ref} described above. *Refms* is an absolute Mach number used for stators and *refmr* is a relative Mach number used for rotors. Should be approximately the largest Mach number expected in the flow. If the code blows up, try increasing *refm* by 0.1. Convergence is mildly sensitive to *refm* and *pck*, so try to keep these values as small as possible.

&nam3 - Boundary Condition & Code Control

Inlet boundary

At the inlet boundary P_0 and T_0 are held constant. For subsonic flow a Riemann invariant based on *u* is extrapolated from the interior. Older versions of Swift held $v\ (v_\theta)$ constant and used a single flag, *ibcin*, to determine how $w\ (v_r)$ was calculated. *Ibcin* is retained for compatibility. If *ibcin* is defaulted, two flags, *ibcinv* and *ibcinw*, determine how *v* and *w* and (v_θ and v_r) are determined. Properties that are held constant are either generated from the initial condition data in the input file or are read directly from a qin-file.

ibcinv	Inlet boundary condition flag for $v\ (v_\theta)$.
	= 1 *v* is held constant. <default>
	= 2 $v/u = \tan\alpha$ is held constant.
ibcinw	Inlet boundary condition flag for $w\ (v_r)$.
	= 1 *w* is held constant. <default>
	= 2 $w/u = \tan\phi$ is held constant.
	= 3 w/u is held tangent to the meridional grid lines at the inlet. <default>
ibcin	Old inlet boundary condition flag. May be For all options $v\ (v_\theta)$ is held constant.
	= 0 or defaulted: ibcinv and ibcinw are used to to set the options.
	= 1 w/u is held tangent to the meridional grid lines at the inlet. <default>
	= 2 Supersonic **meridional** inflow - all quantities are held constant. (Rarely used except for the NASA supersonic throughflow fan project.)
	= 3 $w/u = \tan\phi$ is held constant.
	= 4 *w* is held constant. <default>

Exit Boundary

Four primitive variables are extrapolated to the exit. The input parameter *prat* gives the exit pressure. The parameter *ipex* determines where *prat* is specified and determines how the spanwise pressure distribution is calculated.

ibcex	Exit boundary condition flag.

= 1 *Prat* is specified as a constant. Only applicable to linear geometries, or annular geometries with radial outflow.

= 2 Supersonic **meridional** outflow. *P* is extrapolated to the boundary. *Prat* is not used. (Rarely used except for the NASA supersonic throughflow fan project.)

= 3 *Prat* is specified at the exit. The spanwise variation of $\bar{p}$ is found by solving radial equilibrium. $\bar{p}$ is constant blade-to-blade. <default>

= 4 P*rat* is specified at the exit hub or tip. The spanwise variation of $\bar{p}$ is found by solving radial equilibrium. *P* is found as a perturbation about $\bar{p}$ using a characteristic boundary condition developed by Giles.

ipex Flag that tells where *prat* is specified. This can have a significant effect on the stability range of compressors. For hub-critical machines *ipex* should be set to 0 to hold the hub pressure constant. For tip-critical machines *ipex* should be set to 1 to hold the tip pressure constant.

If *igeom = 0, prat* is held constant over the exit.

= 0 *Prat* is specified at the hub <default.>

= -1 *Prat* is specified at the tip.

= 1 Exit pex-file is read from unit 14. (see "Inlet and Exit Profiles", pp. 13)

Inlet and Exit Profiles

Inlet profiles of P_0, v_θ, v_r and T_0, and exit profiles of p_{stat} can be specified as boundary conditions for Swift. For convenience, a common file format is used for both inlet and exit (see "Inlet and Exit Profiles", pp. 22.) The profiles are input as ascii files containing six variables, P_0, v_x, v_θ, v_r, T_0, and p_{stat} at several spanwise locations. Only the variables needed at a particular boundary are used, and the other variables are ignored. The profiles are interpolated linearly to the span of the actual grid, and should resolve the endwall boundary layers.

Inlet and exit profile files for the current solution can be written by setting variable *ispan=1*. The output file, written to unit 15, can be edited to extract inlet or exit profiles that can used for subsequent calculations. In this way a multistage machine can be modeled one row at a time by using the exit profile from one blade row as the inlet profile to the next.

It may also be useful to modify output profiles manually, for example by replacing core flow quantities at a few points while retaining boundary layer properties.

ispan Flag for writing spanwise profiles to unit 15.

= 0 No output generated. <default>

= 1 Spanwise profile output written to unit 15.

iqin Flag for reading inlet profile.

= 0 Inlet conditions are calculated by *subroutine qincalc* based on the initial condition data, boundary layer thicknesses, etc. in the input file. Current input values are used, so the inlet profiles can be changed at restart if desired. <default>

= 1 Inlet qin-file read from unit 13. Used to read an exit profile from a solution of an upstream blade row.

ipex Flag for reading exit pressure profile, also used to set location of *prat*. (see "Exit Boundary", pp. 12)

= 1 Exit pex-file is read from unit 14.

Code Control

isymt Top-plane symmetry flag. Used to model the bottom half of a linear cascade with bottom-to-top symmetry.

= 1 Symmetry condition on *k = km*.

else Solid wall boundary condition on *k = km*. <default>

kbcor	Flag for order of accuracy used in endwall boundary conditions. Typically 2 (second order), but it is sometimes necessary to use 1 (first order) if points decouple spanwise. This usually only happens on linear geometries with unstretched spanwise grids. <default = 2>
ires	Iteration increment for writing residuals in the output file. Typically 10. If the code is blowing up, set $ires = 1$ to print the size and location of the maximum residual at each iteration.
iresti	Flag for reading input restart file. Restart files are in PLOT3D format.
	= 1 Read restart file from unit 2.
	else No action taken. <default>
iresto	Flag for writing output restart file.
	= 1 Write restart file to unit 3. <default>
	else No action taken.
newkw	Flag for running the k-ω turbulence model from scratch using an unchanging solution. Useful for starting a new k-ω solution from an old Baldwin-Lomax solution.
	= 0 Run k-ω model and flow solver. <default>
	= 1 Run k-ω model from initial guess for *itmax* cycles. Write k-ω file to unit 8 and stop.
kwvars	Number of variables to store in the k-ω file. (See "Turbulence Model k-w File" pp. 22.)
	= 3 Stores 3 variables $[\mu_{tur}, k, \omega]$. Saves storage but not PLOT3D compatible.
	= 5 Stores 5 variables $[\mu_{tur}, k, \omega, Re_t, \mu_{lam}]$. Increases storage but the k-ω file is PLOT3D compatible. <default = 5>

&nam4 **- Flow Parameters**

igeom	Flag for linear cascade or annular blade row.
	= 0 Linear cascade.
	= 1 Annular blade row <default.>
ga	Ratio of specific heats γ. <1.4 for air>
om	Normalized blade row rotational speed, Ω / c_0, where Ω is the wheel speed in radians per second, and c_0 has dimensions of [grid units/sec], giving *om* dimensions of [1/grid units]. The *(x,y,z)* coordinate system must be right-handed. Looking in the positive *x*-direction, clockwise rotation is negative and counterclockwise rotation is positive. Ω is negative for most Glenn geometries. <default = 0.>
prat	Ratio of the exit static pressure to the reference total pressure, $prat = p_{exit}/P_{0r}$.
expt	Exponent used to specify the inlet whirl distribution. $M_\theta = \overline{M_\theta}(r/r_{\mathrm{mid}})^{\exp t}$ where $\overline{M_\theta}$ is the mid-span value of M_θ determined from the initial condition input.
	= 0 Gives uniform M_θ except within the endwall boundary layer. <default>
	= -1 Gives free vortex inflow.
	= 1 Gives forced vortex inflow.

&nam5 - Viscous Parameters

*il*t — Inviscid, Laminar, or Turbulent analysis.

= 0 Inviscid. Most other viscous parameters are not used if *ilt*=0.

= 1 Laminar.

= 2 Turbulent using the Baldwin-Lomax turbulence model. <default>

= 3 Turbulent using the Cebeci-Smith turbulence model. This model works well for turbine heat transfer (4) but may overpredict losses for transonic compressors.

= 4 Fully turbulent using the Wilcox baseline k-ω turbulence model.

= 5 Turbulent with transition using the Wilcox low Reynolds number k-ω turbulence model. Note that "low Reynolds number model" refers to modifications made to give reasonable calculations of flat plate transition, and **not** to near-wall modifications needed by k-ε models.

itur — The turbulence model is updated every *itur* iterations. Recommended values are *itur=5* for the Baldwin-Lomax or Cebeci-Smith models, and *itur=2* for the k-ω model. If the k-ω model blows up quickly it may help to use *itur=1* for the first 100-200 iterations. <default=5>

renr — Reynolds number per unit length based on reference conditions, $renr = \rho_{0r}c_{0r}/\mu_{0r}$. Must have units of $[1/\text{grid units}]$. Generally much larger that a conventional "free-stream" Reynolds number. For example, for standard conditions:

$$renr = 0.0765\left(\frac{\text{lb}_m}{\text{ft}^3}\right)\times 1116.7\left(\frac{\text{ft}}{\text{sec}}\right)/1.285\times10^{-5}\left(\frac{\text{lb}_m}{\text{ft sec}}\right)$$

$$= 6.65\times10^{6}/\text{ft}$$

prnr — Prandtl number. <default = 0.7 for air>

tw — Normalized wall temperature, $tw = T_{\text{wall}}/T_0$.

= 0 Adiabatic wall boundary conditions are used.

= 1 $T_{\text{wall}} = T_0$ <default>

else $T_{\text{wall}} = tw$.

vispwr — Exponent for laminar viscosity power law. <default = 0.667 for air> Use *vispwr=0.0* for water.

$$\mu/\mu_{0r} = (T/T_{0r})^{vispwr}$$

prtr — Turbulent Prandtl number. <default = 0.9>

cmutm — Value of $\mu_{\text{turb}}/\mu_{\text{lam}}$ at which transition is assumed to occur. Baldwin and Lomax recommend 14. Can be increased to move transition downstream or vice-versa. If *cmutm* = 0, the flow is fully turbulent. <default = 14.>

jedge — j-index where the artificial viscosity begins to ramp off near the blade. Also the last j-index searched for the blade turbulent length scale. For the Baldwin-Lomax turbulence model $(ilt = 2)$, *jedge* should be a grid line slightly bigger than the largest expected blade boundary layer. For the Cebeci-Smith turbulence model $(ilt = 3)$, *jedge* should be a grid line slightly bigger than half the largest expected blade boundary layer. <default = 10>

kedgh, kedgt	k-indices where the artificial viscosity begins to ramp off near the hub and tip. Also the last k-indices searched for the hub and tip turbulent length scales. See comments for *jedge*. <default = 10>
iltin	Flag controlling inlet velocity and P_0 profiles. = 0 Inviscid. = 1 Laminar. = 2 Turbulent using Cole's wall-wake profile. <default>
dblh, dblt	Inlet hub and tip boundary layer thicknesses in grid units.
xrle, xrte	Axial locations at which the hub starts and stops rotating, for modeling a rotating drum. Rotational boundary conditions are applied on the hub for $xrle < x < xrte$. Stationary conditions are applied elsewhere. Set $xrle < x_{\text{inlet}}$ and $xrte > x_{\text{exit}}$ to make the entire hub rotate. Note that *xrle* and *xrte* may not be sufficient to locate the rotating part of the disk in a radial flow machine.
tintens	Free-stream turbulence intensity written as a decimal. Used to get the inlet value of k for the k-ω model. <default=0.01, i.e., one percent.>
tlength	Free-stream turbulence length scale. Used to get the inlet value of ω for the k-ω model. Typically $tlength \approx 0.03 \times$ boundary layer height or $tlength \approx 0.001 \times \text{pitch}$. The free-stream turbulent viscosity μ_{tur} is derived from *tintens* and *tlength*, and is printed near the top of the output. Generally μ_{tur} should be ≤ 0.1 to minimize the effects of *tlength*.
hrough	Surface roughness height in turbulent wall units h^+. Implemented in both the Baldwin-Lomax model (*ilt*=2) and the Cebeci-Smith model (*ilt*=3) using the Cebeci-Chang roughness model. $hrough \leq 4.6$ gives a hydraulically-smooth surface. <default = 4.6>

&nam6 **- Output Control**

oar	Flag for frame of reference of output q-file. Swift automatically detects the frame of reference of a restart q-file and converts it to the absolute frame for internal use if necessary. = 0. All blade rows are in the absolute frame of reference. = 1. All blade rows are in the relative frame of reference. <default>
mioe	Flag for output format of mass flow in residual history. For transonic fans the inflow may respond slowly to a change in back pressure, so the inlet mass flow can be monitored for convergence. For turbines the inflow may choke quickly so the outflow can be monitored. In general the mass flow error is a good measure of convergence and accuracy and should converge to a fraction of a percent (e. g., < 0.003). = 1 Inlet mass flow history is written. = 2 Exit mass flow history is written. = 3 Mass flow error $1 - \dot{m}_{\text{out}} / \dot{m}_{\text{in}}$ is written. <default>
iqav	Flag controlling type of θ-averaging used in the output. = 0 Energy average. Mass average of [ρ, V^2, and T]. Usually the most optimistic average.<default> = 1 Momentum average. Mass average of [ρ, ρV, and e], fairly conservative. = 2 Mixed-out average. Formal average of inviscid fluxes gives properties far downstream. Usually the most conservative average.

	= 3 Total pressure average. Converts P_0 to an equivalent T_0, mass averages, then converts back. Often done with experimental data. Usually similar to the energy average.
nko	Number of k-indices for blade surface output, max = 50. <default = 0>
ko	Array of *nko* k-indices separated by commas where blade surface output is desired.
ism	Flag for distance coordinate s used in blade surface output.
	= 0 S = arc length around blade. <default>
	else S = meridional distance along blade.
ile	Flag for location of leading edge (s=0) used in blade surface output.
	= 0 S = 0 at i = imax/2 index. <default>
	else S = 0 at smax/2.

Initial Condition Input

Immediately following the namelist input comes *nrow+2* lines of data used for the initial guess and the inlet boundary conditions. *Nrow* is the number of blade rows and is determined within Swift by counting the number of lines of input.

The first line is ignored and can be used for column labels. Subsequent lines give row number and nominal flow conditions at mid-span. Unformatted reads are used, so all variables must be input.

A sample initial condition input for a seven-block grid is shown in figure 3. A portion of the input is repeated below.

```
row        P0         Mx         Mt         Mr         T0
  0    1.0000      .1330    -.0000         0.    1.0000
  1     .9938      .1692    -.3986         0.    1.0000
 etc.
```

The variables are as follows:

row	Integer blade row number. Row number 0 is the inlet. Subsequent row numbers represent the exits of each blade row.
P0	Meanline P_0/P_{0r}.
Mx	Meanline Mach number in the x-direction.
Mt	Meanline Mach number in the θ- or y-direction.
Mr	Meanline Mach number in the r- or z-direction.
T0	Meanline T_0/T_{0r}.

Index File

The index file is an ascii file that gives the grid sizes, connectivity, and certain boundary condition information for each grid. It replaces namelist block &nl1 in RVC3D.

The first line is ignored and can be used for column labels. Subsequent lines give grid type, dimensions, key indices (like *itl* and *iil* in RVC3D), connecting grid numbers, blade row number, and relative rotational rate for each grid. Negative values are sometimes used to toggle boundary condition options. One line is required for each grid. Unformatted reads are used, so all variables must be input.

For an isolated blade row, TCGRID will produce a complete index file written to unit 10. It may be necessary to modify *nhub* or *ntip* if the simple periodicity clearance model is to be used, or to modify the rotation multipliers *om*, *omh*, or *omt.*

For multistage calculations the grids for each blade row are generated separately, and merged using the utility code MULTIX. The separate index files must be merged manually using the unix *cat* command or an editor. Extraneous header lines must be removed, and connectivity information must be added manually.

A sample index file for a seven-block grid is shown in figure 3. A portion of the file is repeated below.

```
 grid type   im   jm   km   i1   i2   i3  nin  nex nhub ntip nlr row  om omh omt
    1    1   17   17   57    0    0    0  999    2    0    0   0   1  0.  0.  0.
    2    2  127   37   57   14   57    0    1   -3    0    0   0   1  0.  0.  0.
etc.
```

Index File Variables

grid	Grid (block) number, from 1 to number of grids	
type	Flag giving type of grid.	
	= 1	H grid for upstream
	= 2	C grid for blades
	= 3	O grid for hub or tip clearances
im	Number of grid points in i-direction.	
jm	Number of grid points in j-direction.	
km	Number of grid points in k-direction.	
i1	C-grid:	Lower i-index of trailing edge. Upper index is assumed to be periodic.
	else:	Not used.
i2	C-grid:	Lower i-index of inlet (or last periodic point.) Upper index is assumed to be periodic.
	else:	Not used.
i3	C-grid:	k-index where hub clearance ends, or
	C-grid:	k-index where tip clearance starts.
	Used with simple periodicity clearance model (*nhub* or *ntip* = -1.)	
	Used to set limits on turbulence models for gridded clearance regions (*nhub* or *ntip* > 0.)	
nin	Inlet boundary condition flag.	
	nin = 999:	C- or H-grid with conventional inlet boundary condition.
	nin > 0:	C-grid inlet patched to upstream H-grid number nin.
	nin < 0:	C-grid inlet mixed-out from upstream C-grid number nin
nex	Exit boundary condition flag.	

	nex = 999: C-grid with conventional exit boundary condition.
	nex > 0: H-grid exit patched to downstream C-grid number nex.
	nex < 0: C-grid exit mixed out to downstream C-grid number nex.
nhub	nhub > 0: C-grid patched to O-grid number nhub.
	nhub = -1: C-grid with simple periodicity hub clearance model between k=1 and k=i3.
ntip	ntip > 0: C-grid patched to O-grid number ntip.
	ntip = -1: C-grid with simple periodicity tip clearance model between k=i3 and k=km.
	Note: Swift currently can model either hub clearances or tip clearances, but not both simultaneously. This will be corrected in a future release.
nlr	Not currently used.
row	Integer blade row number between 1 and the number of rows. Corresponds to row number in initial condition input.
om(n)	Rotation multiplier. The rotational speed for this grid is $om \times om(n)$. Usually 0.0 for stators, 1.0 for rotors, or -1.0 for counterrotating rotors. (See “&nam5 - Viscous Parameters” pp. 15 for definition of normalized blade row rotational speed *om*.)
omh	Hub rotation multiplier. Rotational speed for k=1 on this grid is $om \times omh$. Usually 1.0 for rotating hubs. Overridden by variables *xrle* and *xrte*, the axial locations at which the hub starts and stops rotating (see “&nam5 - Viscous Parameters”, pp. 15.)
omt	Tip rotation multiplier. Rotational speed for k=km on this grid is $om \times omt$. Usually 0.0 for stationary shrouds or 1.0 for rotating shrouds.

Swift Output

Printed output from Swift is written to Fortran unit 6 (standard output.) The output is divided into several sections. The sections may be separated using an editor and plotted using any x-y plotting package that can read ascii column data.

1. The input variables are echoed back for reference, and any comments or warnings regarding the input are given.

2. Spanwise profiles of θ – averaged flow variables are given at the inlet or exit. These variables are either based on the initial guess or on a restart file, depending on how the code is started. The initial profiles are often useful for identifying grid lines near endwall boundary layers.

3. A convergence history gives maximum and RMS residuals of density, and exit flow properties versus iteration.

4. Spanwise profiles of θ – averaged flow variables are repeated at the inlet and exit for the new solution. Four different averaging schemes are available for computing these profiles.

5. Blade surface profiles of various quantities are given on selected k grid lines (spanwise locations.) Values of y^+ for the first grid point are given for checking turbulent grid spacing, and maximum values of μ_T are given to identify transition points.

Test Cases

Goldman Turbine Vane

The first test case is an for an annular turbine vane tested by Goldman at NASA Glenn Research Center. Computed results were presented in references 2 and 4, and are shown here in figure 4.

The grid is shown at the top left of the figure. The grid size was $97 \times 32 \times 33$, for a total of 102,432 points. The grid size is intentionally coarse is to make the test case run quickly, but the results are still very good.

The solution was run with the standard four-stage Runge-Kutta scheme with cfl=5.6 and eps=0.75. The k-ω turbulence model was used. The calculations were run 1500 iterations, which took about 45 minutes on an SGI Octane with an R12000 processor running at 300 MHz.

Convergence histories are shown at the bottom left. Exit total pressure converges to three significant digits in about 1000 iterations, and mass flow error $1 - \dot{m}_{out} / \dot{m}_{in}$ converges to about 0.001.

Mach contours at midspan are shown at the top right. The flow is entirely subsonic. The thin boundary layers and wake are evident.

Comparisons with experimentally-measured exit profiles are shown at the bottom right. The computed total pressure loss is slightly high, but improves on a finer grid as shown in (4.)

NASA Rotor 67

The second test case is an for a low aspect ratio transonic fan denoted NASA rotor 67 that was also tested at NASA Glenn Research Center. Computed results were presented in (3) and are shown here in figure 5.

A three-block grid was used, as shown at the top left of the figure. The upstream H-grid was $25 \times 19 \times 49$, the C-grid around the blade was $187 \times 37 \times 49$, and the O-grid in the tip clearance was $147 \times 11 \times 7$, for a total of 373,625 points. This grid size is quite adequate.

The solution was run with the standard four-stage Runge-Kutta scheme with cfl=5.6 and eps=0.75. The Baldwin-Lomax turbulence model was used. The calculations were run 1500 iterations, which took about 3.7 hours on an SGI Octane with an R12000 processor running at 300 MHz.

Convergence histories are shown at the bottom left. Inlet mass flow and exit total pressure converge to three significant digits in about 1000 iterations. The mass flow error was < 0.0003.

The pressure ratio prat was chosen to give an operating point near peak efficiency. Mach contours at 90 percent span are shown at the top right. The bow shock system and passage shock can be seen.

Comparisons with experimentally-measured exit profiles are shown at the bottom right. All exit profiles are in excellent agreement with the experimental data.

File Descriptions

Grid *XYZ*-File

Grids are stored using standard PLOT3D xyz-file format. Grids can be read with the following Fortran code:

```
c      read grid coordinates
       read(1)im,jm,km
       read(1)(((x(i,j,k),i=1,im),j=1,jm),k=1,km),
     &        (((y(i,j,k),i=1,im),j=1,jm),k=1,km),
     &        (((z(i,j,k),i=1,im),j=1,jm),k=1,km)
```

Solution Q-File

Solution files are stored in standard PLOT3D q-file format. Solution files can be read with the following Fortran code:

```
c      read q-file
       read(2)im,jm,km
       read(2)eminf,aldeg,renr,time
       read(2)((((qq(l,i,j,k),i=1,im),j=1,jm),k=1,km),l=1,5)

c      additional geometry data and residual history
       read(2)itl,iil,phdeg,ga,om,nres,igeom,dum,dum,dum
       read(2)((resd(n,l),n=1,nres),l=1,5)
```

The q-variables are:

$$q = \left[\frac{\rho}{\rho_{0r}}, \frac{\rho u}{\rho_{0r}c_{0r}}, \frac{\rho v}{\rho_{0r}c_{0r}}, \frac{\rho w}{\rho_{0r}c_{0r}}, \frac{e}{\rho_{0r}c_{0r}^2}\right]$$

$$e = \rho\left(C_v T + \frac{1}{2}(u^2 + v^2 + w^2)\right)$$

If *oar=1* the relative velocity components are stored, $v' = v - \Omega z$, $w' = w + \Omega z$ ..

Turbulence Model k-ω File

Restart files for the k-ω turbulence model are stored in standard PLOT3D q-file format. Solution files can be read with the following Fortran code:

```
c      read tmu, k, w
       read(7)im,jm,km
       read(7)dum
       read(7)((((tkw(l,i,j,k),i=1,im),j=1,jm),k=1,km),l=1,kwvars)
```

The tkw-variables are:

$$tkw = \left[\frac{\mu_{tur}}{\mu_{0r}}, \frac{k}{c_{0r}^2}, \frac{\omega}{c_{0r}}, \frac{\mu_{lam}}{\mu_{0r}}, Re_{tur}\right]$$

Note that the laminar viscosity μ_{lam} and the turbulence Reynolds number Re_{tur} are not used by Swift. They are written to pad the file for PLOT3D compatibility if *kwvars=5.* This results in larger file sizes than necessary. Smaller files may be generated by setting *kwvars=3*, but the files cannot be read by PLOT3D.

Inlet and Exit Profiles

Inlet profiles of P_0, v_θ, v_r and T_0, and exit profiles of p_{stat} can be specified as boundary conditions for Swift. For convenience, a common file format is used for both inlet and exit. The profiles are input as ascii files containing six variables, P_0, v_x, v_θ, v_r, T_0, and p_{stat} at several spanwise locations. Only the variables needed at a particular boundary are used, and the other variables are ignored. The profiles are interpolated linearly to the span of the actual grid, and should resolve any desired endwall boundary layers.

A sample profile file can be generated by setting variable *ispan=1*. The output written to unit 15 may be edited manually to extract the desired profile. The format is as follows:

```
&ospan irow = 0 kin = 95 flow = 119.25082 &end
k    s/span    P0/P0i     vx/c0    vth/c0     vr/c0    T0/T0i    ps/P0i
1   0.00000   1.12907   0.00000  -0.65789   0.00000   1.06326   0.83876
2   0.00019   0.90181  -0.07050  -0.31211  -0.01668   1.00000   0.83864
etc.
```

The first line is namelist input. Only *kin* is required.

kin	Number of spanwise points.
irow	Dummy variable not used by Swift, but useful for identifying the desired profile from an output file. *Irow* gives the relative location of the profile, where *irow=0* is the inlet, *irow=1* is the exit of the first blade row, *irow=2* is the exit of the second blade row, etc.
flow	Dummy variable not used by Swift. *Flow* is the non-dimensional mass flow and is included for use by the CSTALL code now under development.

The second line has titles for convenience but is not read. The remaining *kin* lines have the following variables:

k	Spanwise index, not used.
s/span	Normalized spanwise distance, between 0.0 at the hub to 1.0 at the tip.
P0/P0i	Normalized total pressure, used for inlet profiles only.
vx/c0	Normalized axial velocity, not used.
vth/c0	Normalized tangential velocity, used for inlet profiles only.
vr/c0	Normalized radial velocity, used for inlet profiles only.
ps/p0i	Normalized static pressure, used for exit profiles only.

References

1. Baldwin, B. S., and Lomax, H., “Thin-Layer Approximation and Algebraic Model for Separated Turbulent Flows,” AIAA Paper 78-257, Jan. 1978.

2. Chima, R. V., Yokota, J. W., “Numerical Analysis of Three- Dimensional Viscous Flows in Turbomachinery,” AIAA J., Vol. 28, No. 5, May 1990, pp. 798-806.

3. Chima, R. V., “Viscous Three-Dimensional Calculations of Transonic Fan Performance,” in CFD Techniques for Propulsion Applications, AGARD Conference Proceedings No. CP-510, AGARD, Neuilly-Sur-Seine, France, Feb. 1992, pp 21-1 to 21-19. Also NASA TM-103800.

4. Chima, R. V., Giel, P. W., and Boyle, R. J., “An Algebraic Turbulence Model for Three-Dimensional Viscous Flows,” in *Engineering Turbulence Modeling and Experiments 2*, Rodi, W. and Martelli, F. editors, Elsevier pub. N. Y., 1993, pp. 775-784. Also NASA TM-105931.

5. Chima, R. V., “A k-ω Turbulence Model for Quasi-Three-Dimensional Turbomachinery Flows,” AIAA Paper 96-0248, Jan. 1996. Also NASA TM-107051.

6. Chima, R. V., “Calculation of Tip-Clearance Effects in a Transonic Compressor Rotor,” J. Turbomachinery, Vol. 120, Jan. 1998, pp. 131- 140. Also NASA TM107216.

7. Tweedt, D. L., Chima, R. V., and Turkel, E., “Preconditioning for Numerical Simulation of Low Mach Number Three-Dimensional Viscous Turbomachinery Flows,” AIAA Paper 97-1828, June, 1997. Also NASA TM-113120.

8. Chima, R. V., “Calculation of Multistage Turbomachinery Using Steady Characteristic Boundary Conditions,” AIAA Paper 98-0968. Also NASA TM-1998-206613.

9. Chima, R. V., “TCGRID 3-D Grid Generator for Turbomachinery - User’s Manual and Documentation,” Dec. 1999, available from the author.

10. Jameson, A., Schmidt, W., and Turkel, E., “Numerical Solutions of the Euler Equations by Finite Volume Methods Using Runge-Kutta Time-Stepping Schemes,” AIAA Paper 81-1259, June 1981

11. Sorenson, R. L., “A Computer Program to Generate Two- Dimensional Grids About Airfoils and Other Shapes by Use of Poisson’s Equation,” NASA TM-81198, 1980.

12. Turkel, E., “A Review of Preconditioning Methods for Fluid Dynamics,” *Applied Numerical Mathematics*, Vol. 12, 1993, pp. 257-284.

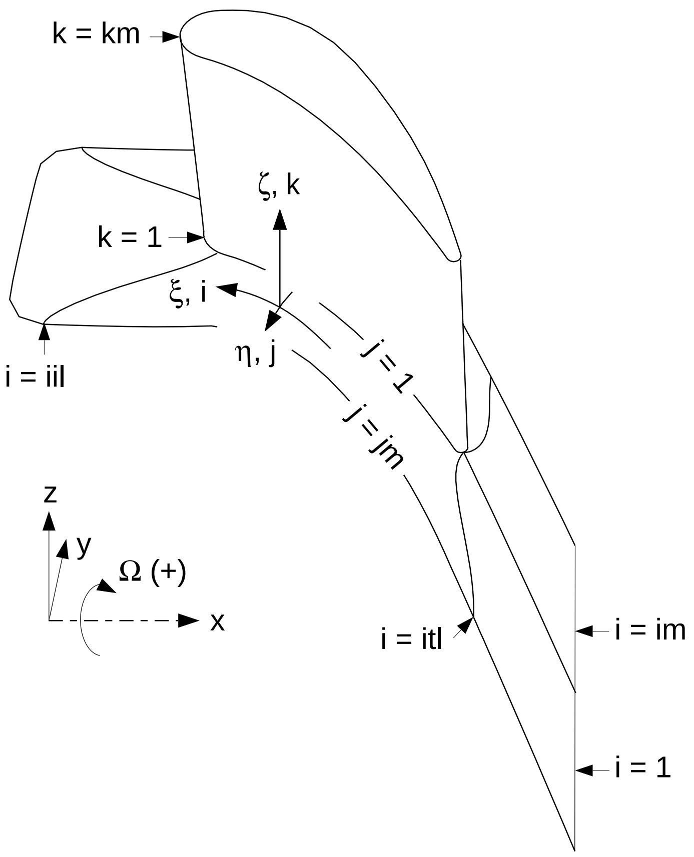


Figure 1 — Body-fitted coordinate system and index conventions for a turbine vane grid.

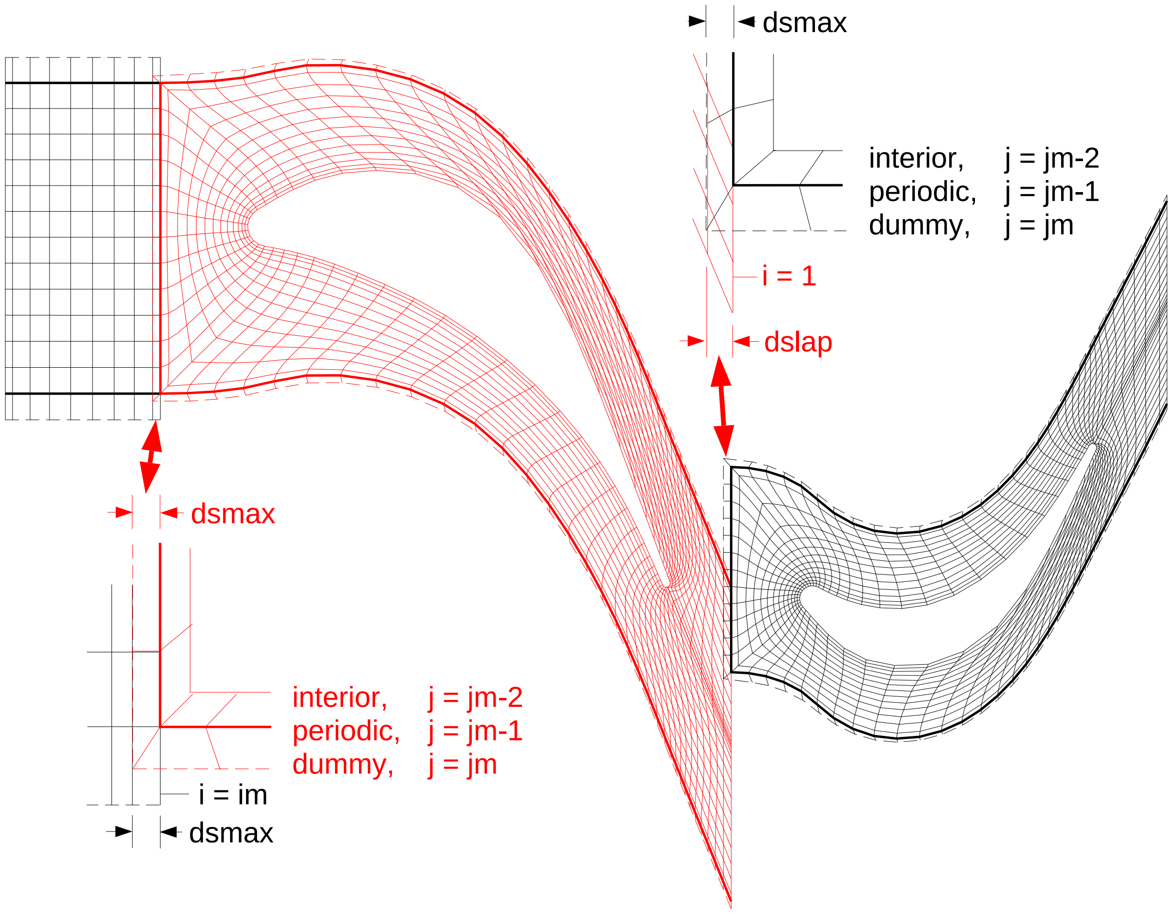
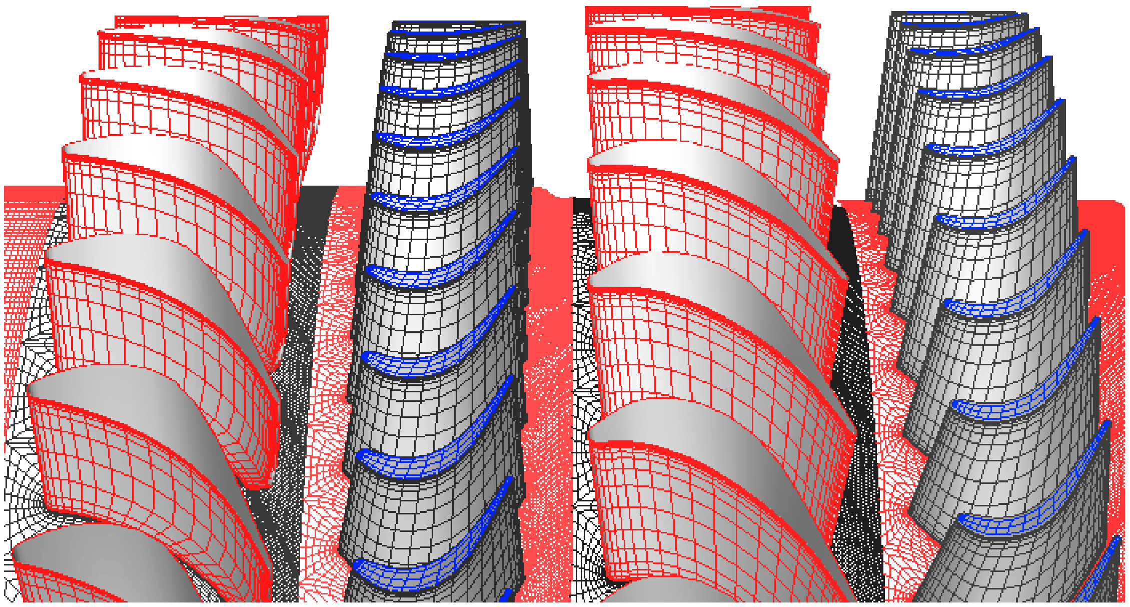
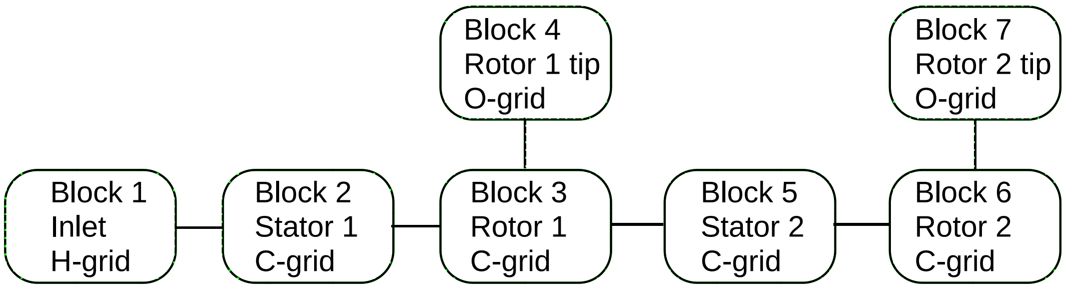


Figure 2 — Three-block grid for a turbine stage showing overlap regions and dummy grid lines.



Seven-block grid for a two-stage turbine with rotor tip clearances.



Block diagram of a seven block grid..

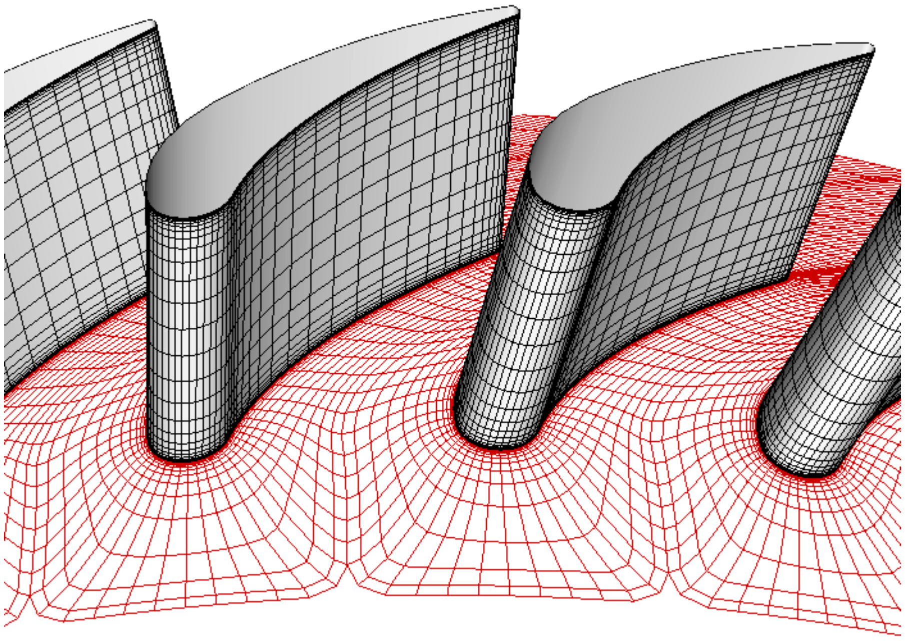
```
grid type   im   jm   km   i1   i2   i3  nin  nex nhub ntip nlr row  om omh omt
   1    1   17   17   57    0    0    0  999    2    0    0   0   1  0.  0.  0.
   2    2  127   37   57   14   57    0    1   -3    0    0   0   1  0.  0.  0.
   3    2  127   33   57   17   57   45   -2   -5    0    4   0   2  1.  1.  0.
   4    3   95   13   13    0    0   45    0    0    0    3   0   2  1.  1.  0.
   5    2  127   37   57   14   55    0   -3   -6    0    0   0   3  0.  0.  0.
   6    2  141   33   57   21   64   45   -5  999    0    7   0   4  1.  1.  0.
   7    3  101   13   13    0    0   45    0    0    0    6   0   4  1.  1.  0.
```

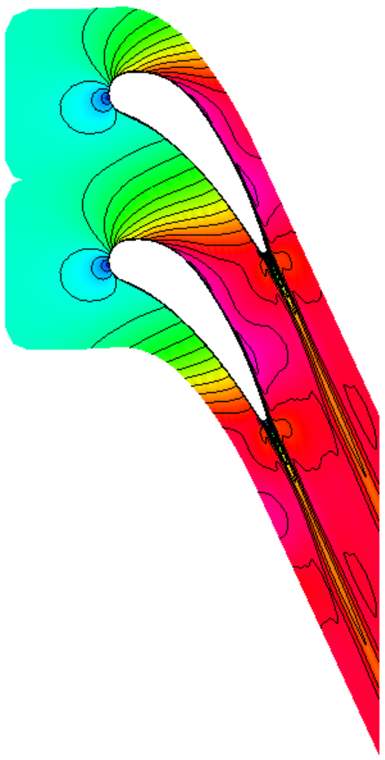
Index file

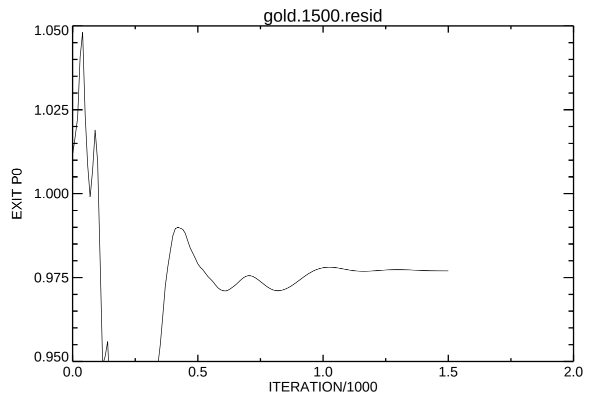
```
row       P0       Mx       Mt       Mr       T0
  0   1.0000    .1330   -.0000       0.   1.0000
  1    .9938    .1692   -.3986       0.   1.0000
  2    .8210    .1984    .0802       0.    .9518
  3    .8112    .1858   -.4175       0.    .9518
  4    .7964    .3693    .0852       0.    .9059
```

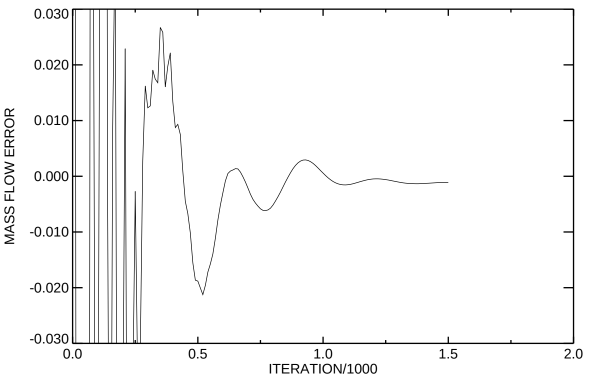
Initial condition data.

Figure 3 — Grid, block diagram, index file, and initial condition data for a two-stage turbine with rotor tip clearances.

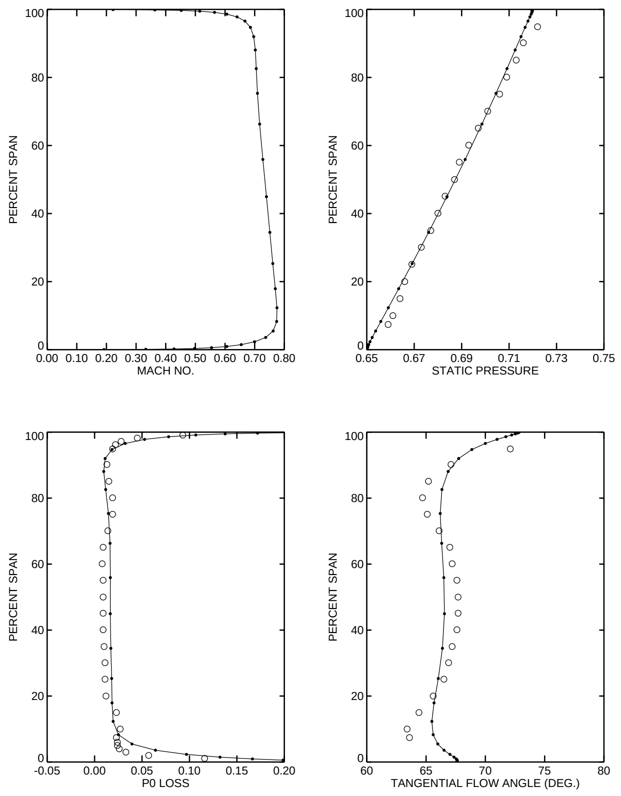

97 x 32 x 33 computational grid


Mach number contours at midspan



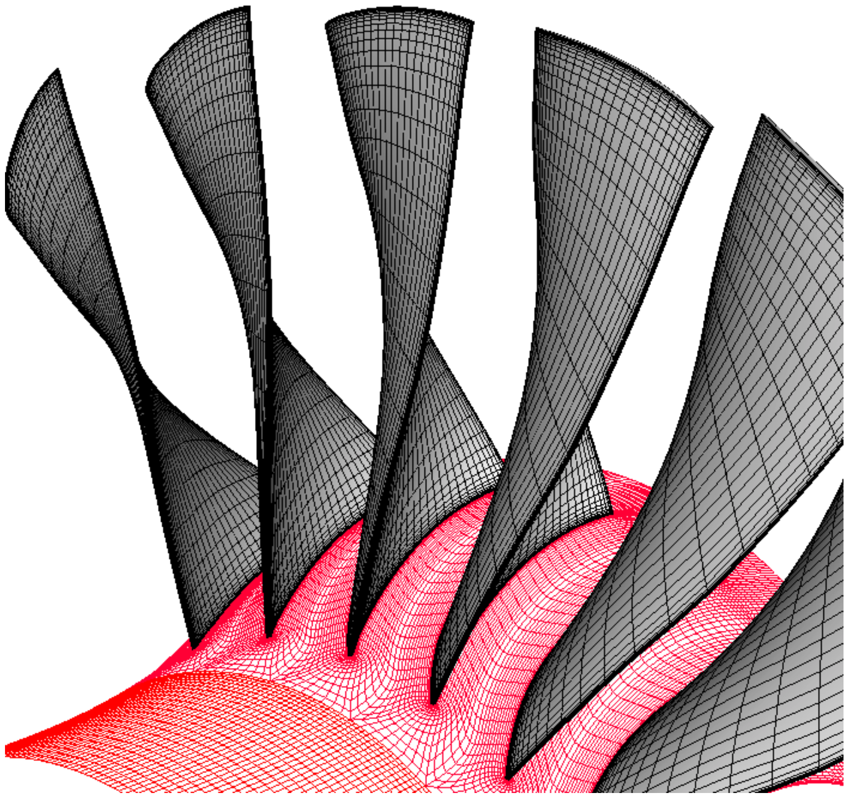


Convergence histories

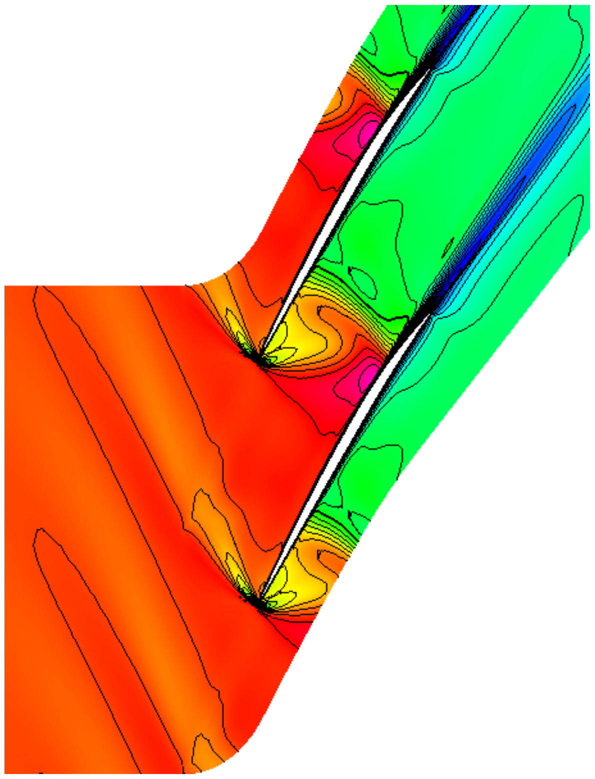


Comparison of computed and measured exit profiles

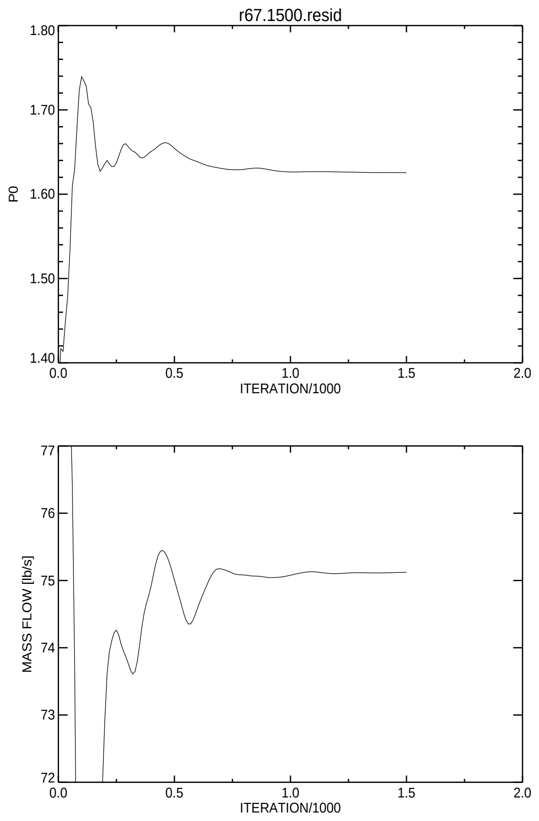
Figure 4 — Goldman annular turbine vane test case



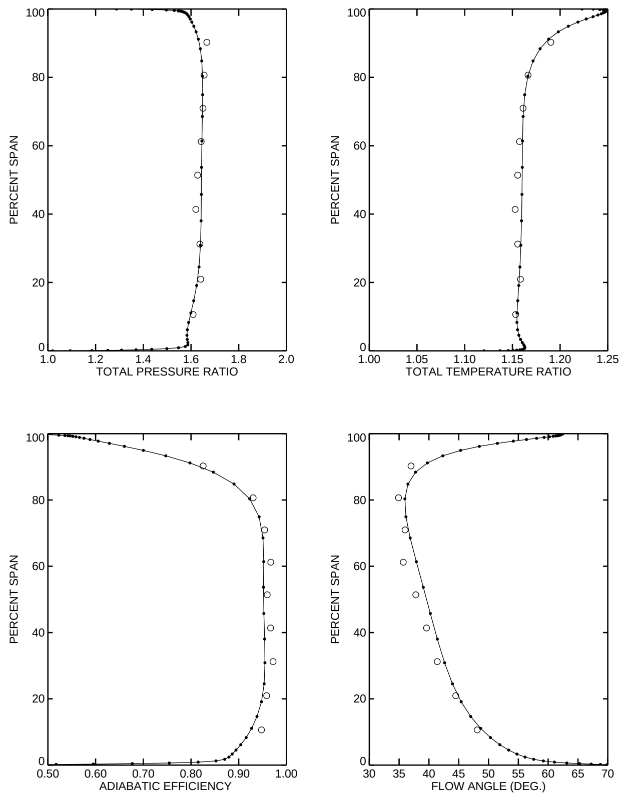
Multiblock grid



Mach number contours at 90 percent span



Convergence histories



Comparison of computed and measured exit profiles

Figure 5 — NASA rotor 67 test case